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CHAPTER 5

INSULATING MATERIALS FOR CABLES

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1.0 INTRODUCTION

Electrical insulation materials are employed over the metallic conductors of underground cables at all voltage ratings. Polymeric materials are employed as the insulation, but the nature of the polymer may vary with the voltage class.

Transmission cables, which are defined as cables operating above 46 kV, have traditionally used paper / oil systems as the insulation. The paper is applied as a thin film wound over the cable core. Some years back, a variation of this paper insulation was developed, the material being a laminate of paper with polypropylene (PPP or PPLP). Since the advent of synthetic polymer development, polyethylene (PE) has been used as an insulation material, and in most countries (France being the exception) the use of polyethylene was limited to the crosslinked version (XLPE). XLPE is considered to be the material of choice due to its ease of processing and handling, although paper / oil systems have a much longer history of usage and much more information on reliability exists.

For distribution voltage classes (mostly 15 to 35 kV), the prime material used in the past was conventional PE; however, this was replaced by XLPE as the material of choice in the 1980s. The installed PE-insulated cables are gradually being replaced. In recent years, ethylene propylene co- or ter-polymers have been used (EPR or EPDM, respectively). The use of EPR, which is an elastomer, (XLPE is semi-crystalline) requires the incorporation of inorganic mineral fillers. The term EPR has been used to generically describe both EPR and EPDM cables and that terminology will be employed here.

At even lower voltages, the possible choices of polymeric materials widens. Here it is possible to use polyvinyl chloride (PVC), silicone rubber (SIR), or other polymers that are readily available and processable. PVC was used for a time in Europe for medium voltage cables in the 10 kV class, but that practice has been discontinued.

Many years ago, butyl rubber was used for distribution cables, but virtually all of this installed cable has been replaced at medium voltages.

Each insulation type has certain advantages and disadvantages. As an overview, some are noted below:

<u>POLYMER TYPE</u>	<u>PROPERTY</u>
Low Density Polyethylene	Low dielectric losses Moisture sensitive under voltage stress
Crosslinked polyethylene	Slightly higher losses vs. PE Ages better than PE
EPR / EPDM	Higher losses vs. XLPE or PE More flexible than XLPE or PE Requires inorganic filler
PVC	Must contain plasticizer for flexibility Higher losses

Polymers such as polyethylene, polypropylene, and ethylene propylene co- and ter-polymers are hydrocarbon polymers, and are known as polyolefins. Paper insulated cables were historically the first type of polymer used since paper was, and is, readily available from natural resources. Paper is derived from wood pulp and is a natural polymer comprised of cellulose. However, the polyolefins developed shortly after World War II are a preferred insulation because of their superior properties such as:

- ☐ Excellent electrical properties
 - Low dielectric constant
 - Low power factor
 - High dielectric strength
- ☐ Excellent moisture resistance
- ☐ Extremely low moisture vapor transmission
- ☐ High resistance to chemicals and solvents

The electrical properties of polyolefins are superior to those of paper / oil insulation systems and the polymers are considerably more moisture resistant than paper. The reasons for preferred use of polyolefins for electrical insulations are clear.

In addition to the primary insulation, polymers are employed as conductor and insulation shields. These are essentially ethylene copolymers that possess quantities of carbon black to provide the conducting properties. The copolymer

is considered a "carrier", but this carrier must possess the property of controlled adhesion to the insulation. The use of a conducting material dispersed throughout the polymer matrix makes the mixture semiconducting in nature; hence the term "semiconducting" is applied to the shield materials.

This chapter will focus on:

- (a) Fundamental properties of polyethylene and crosslinked polyethylene from an electrical perspective.
- (b) EPR and how it differs from PE and XLPE.
- (c) Fundamentals of cellulosic insulation and how it differs from polyolefins.

2.0 FUNDAMENTALS OF EXTRUDED POLYMERS

2.1 Polyethylene

Polyethylene is a hydrocarbon polymer comprised exclusively of carbon and hydrogen. It is manufactured from the monomer ethylene, as shown in Figure 5-1. Note that the chemical structure is a series of repeating - CH₂ - units.

Figure 5-1

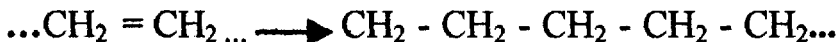
FUNDAMENTALS

■ Polyethylene

■ Crosslinked polyethylene

Ethylene (gas)

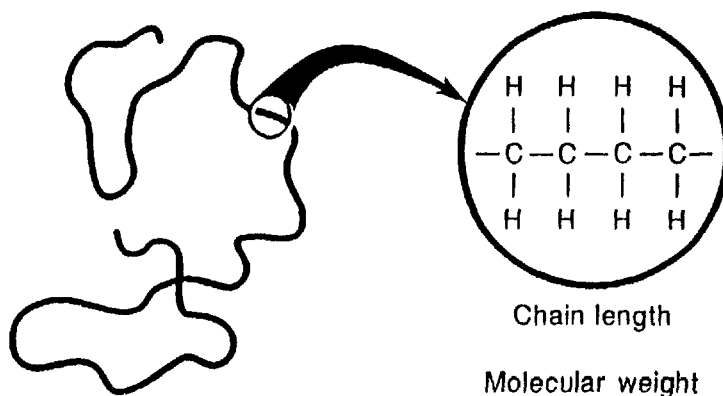
Polyethylene (solid)



Polyethylene falls into the class of polymers known as polyolefins (polypropylene is another example). The polymer is produced by one of several processes, the nature of which is beyond the scope of this book. What is important to note is that the method of manufacture controls the exact chemical structure, which in turn controls the properties. The carbon--hydrogen structure noted above is simplified; PE is actually more complex than is shown here. To

understand this, and for simplicity, we will depict the polymer as a wavy line as shown below in Figure 5-2.

Figure 5-2
Depiction of Polyethylene Chemical Structure



The wavy line is referred to as a “chain” and the length of the chain is significant. The chain length as depicted is related to the molecular weight. Hence, a longer chain is considered to have a higher molecular weight than a shorter chain. Molecular weight increases as the number of ethylene groups in the molecule increases. Conventional polyethylene is comprised of many chains of this type, and the chain lengths varies. Hence, PE is considered to be comprised of polymer chains that have a distribution of molecular weights. Indeed, the molecular weight distribution is a means of characterizing the polyethylene. For the PE insulation that was employed as insulation for medium voltage cables in the past, the polymeric material was described as “high molecular weight polyethylene.” This merely means that the “average” chain length was considered to be high. Another generalization is that the higher the molecular weight, the better the overall properties. A typical polyethylene contains a variety of individual chains of different lengths (i. e., weights).

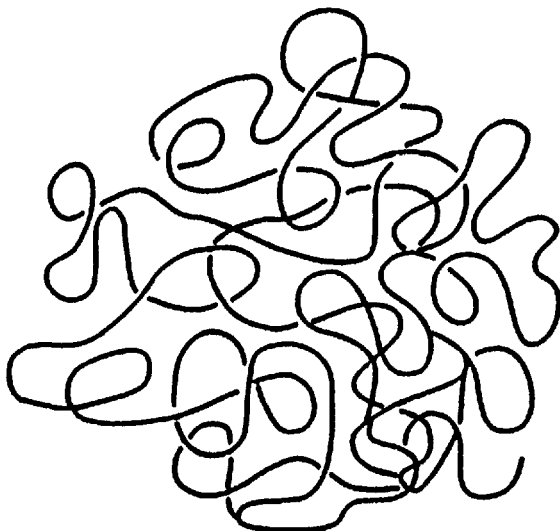
The average molecular weight can be described in several ways. The terms employed most often are “weight average” and “number average.” These values arise from different mathematical methods of averaging the molecular weights in polymer samples possessing molecules of different sizes. The mathematical definitions of the number and weight averages are related to the smaller and larger sized molecules, respectively. Hence, the weight average molecule weight is always greater than the number average. When the polymer insulation is crosslinked (see below), the molecular weight determination becomes more complex since the crosslinked fraction can be considered to have an “infinite”

molecular weight. From the perspective of the cable engineer, what is relevant to understand is that there is no single way of characterizing the polymer molecular weight. However, the higher molecular weight (average, of course) provides better overall properties in application.

The same principles apply to ethylene copolymers with propylene or other monomers such as vinyl acetate or ethyl acrylate. These latter copolymers are employed in shield compounds. The chain lengths may vary and their length influences properties. The relative amounts of the second (copolymerized) monomer must also be taken into consideration when evaluating properties.

Another point to note about the polyethylene chains is the fact that they have a tendency to coil. In other words, they are not exactly straight, but have a tendency to achieve random configuration like a bowl of spaghetti as shown in Figure 5-3. This tendency is independent of the molecular weight.

Figure 5-3
Simplified Description of Random Coiled Configuration

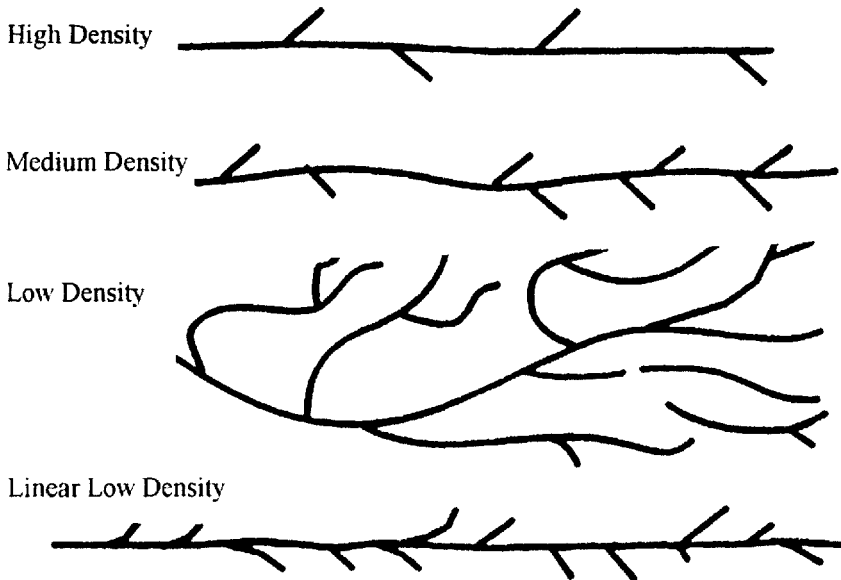


The tendency to coil means that the chains also have a tendency to entangle with each other. These entanglements mean that when the chains are pulled apart (as would occur in performing a tensile strength or elongation measurement), and there will be some resistance to movement. These entanglements contribute to the good properties of PE, but not to the qualities that make PE resistant to the penetration of water vapor.

In addition, the chains are not always as linear as shown in the figures. When

polyethylene is manufactured, the process always leads to side chains coming off the main long chain. This is called chain branching, and is discussed below. These branches contribute to the molecular weight. It is possible to now visualize that two single molecules may have the same exact molecular weight, but one may have a longer main chain and the other a shorter main chain with a longer branch than the first. Two different polyethylene material batches having many molecules like the two described here (if it were possible to manufacture these) would have significantly different properties.

Figure 5-4
Structure of Polyethylenes



Molecular weight, or molecular weight distribution, is one way of describing the characteristics of polyethylene insulation, but it is not the only way. Other very important characteristics are branching and crystallinity. Crystallinity will be discussed first. Polyethylene and some other polyolefins are known as semicrystalline polymers. This characteristic results from the fact that the polymer chains have a tendency not only to coil, but to align relative to each other. Alignment means that there is short and long term order to the chain structure. While the nature of these alignments is quite complex, and the detailed structure is beyond the scope of this chapter, it is important to understand that the alignment contributes to the crystalline nature of the polyethylene, and therefore to the density.

Figure 5-5

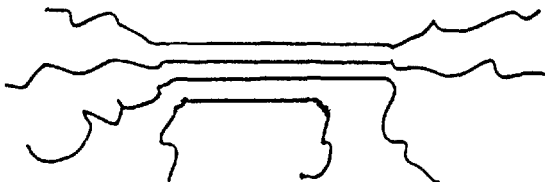
Conventional polyethylene has many chains



The chains have a tendency to coil



For polyethylene, different chain segments also have a tendency to align next to each other



The aligned portions cannot coil. The portions that are not aligned will coil. The chain portions that are aligned are said to be crystalline. The chain portions not aligned are said to be amorphous.

Figure 5-5 shows chains alignment where the polymer chain lengths differ. Some portions of the same chains align with adjacent chains, and some portions of the very same chains are not aligned. Those chain portions where alignment occurs are in regions called "crystalline." Figure 5-5 shows that such alignment is not related to molecular weight. It is possible to have low or high molecular weight polyethylene of the same, or different, degrees of alignment. Hence, in principle, it is possible to have many different types of polyethylenes: high density, high molecular weight; high density, low molecular weight; low density, high molecular weight; or low density, low molecular weight. Not all these types are of practical interest.

It is the crystalline regions that give polyethylene many good properties such as toughness, high modulus, moisture and gas permeation resistance. Those regions

that are aligned also have increased density due to "tighter" chain packing. Hence, increased crystallinity also means higher density. The alignment process means less "free" (amorphous) regions in the polymer and more polymer per unit volume. The amorphous regions increase the ductility, flexibility, and facilitate processing.

Branching, referred to above, is a direct result of the polymerization process. The older high pressure process leads to a greater number of branches (and they are longer) than do the newer low pressure processes. Branching influences the crystallization process by interfering with the ability of the polyethylene chains to align with each other. For crystallinity to occur, non-branched regions must be able to approach each other closely. When branching is present, the ability of the main chain to come in close proximity to another main chain is inhibited. Hence, polyethylenes have historically been classified into three main categories due to this phenomenon:

Low density
Medium density
High density

As the density increases, the degree of chain alignment increases and the "volume" of aligned chains increases. The degree of branching is related to the polymerization process. It is affected since branching influences crystallinity, the latter is affected very little, if at all, by the conversion of polymer pellets into cable insulation.

Historically, low and medium density polyethylenes have been manufactured by a high pressure process, and high density polyethylene by a low pressure process using a different catalyst concept. Manufacturing technology is continuously changing. More recently, suppliers have been able to manufacture a low to medium density polyethylene by a low pressure process. This product has been called linear low density polyethylene, or LLDPE. Even more recently, changes in catalyst polymerization technology have allowed manufacturers to carefully control the molecular weight and molecular weight distribution. This has led to development of newer grades of polyethylene having very well controlled molecular weight distribution and very low density. Low pressure polymerization techniques today can lead to polyethylenes with many short branches and compounds (such as 1-butene or 1-hexene) are used to facilitate the control of the branching and therefore the crystallinity.

By now, it should be clear that polyethylene is a very complex material. Its apparent simplicity; i.e., a composition consisting solely of repeating $-CH_2-$ functional groups, belies the fact that the actual polymer is comprised of segments imparting significantly different properties. The alignment of some of

the chains imparts crystallinity. The non-aligned fractions can coil and are called the amorphous regions. The polymer itself is therefore a "mixture" of different physical segments. That is why it is referred to as "semicrystalline."

The amorphous regions, having relatively large distances between the polymer chains relative to the crystalline regions, are sites where foreign ingredients can reside. Such foreign contaminants can be not only dirt but ions. The crystalline regions, having aligned chains and being closer together than the amorphous regions, are the regions that resist residing of foreign ingredients and penetration of gases. The crystalline regions provide the toughness and resistance to environmental influences. However, without the amorphous regions mixed in, it would not be possible to extrude the polymer into a functional insulation.

What causes different polyethylenes to have different ratios of crystalline to amorphous regions? Any component present on the polymer chain (backbone) that induces chain separation will decrease the degree of crystallinity. Hence, a copolymer of ethylene with propylene, for instance, will decrease the number of consecutive methylene links in the chain and increase the tendency for the chains to be more amorphous. This suggests that EPR would be less crystalline than PE. This is exactly the case. The extent to which this occurs will be dependent upon the ethylene to propylene ratio present. One may wonder therefore, how the "lack" of crystallinity is compensated for in a completely or almost completely amorphous polymer. The answer is that inorganic fillers are incorporated to provide the needed "toughness" in amorphous insulations.

A second factor contributing to influencing the degree of crystallinity is, as noted earlier, the tendency for the chains to have branches. The conventional high pressure process of manufacturing polyethylene (from ethylene monomer) facilitates the formation of branches on the backbone. The branches can have different chain lengths themselves. This is depicted in Figure 5-4. It is the degree and nature of the branches in conventionally manufactured polyethylene that influences the degree of branching and therefore the tendency to align and, in turn, influences the density and crystallinity. It is for this reason that there are such a large variety of different densities available. Until the mid 1980s or thereabouts, high molecular weight, low density polyethylene was a material of choice for many users. This polymer has been replaced for new installations by crosslinked polyethylene and other materials such as EPR and tree resistant crosslinked polyethylene. Medium and high density polyethylenes have traditionally been used as components for cable jackets in medium voltage cables.

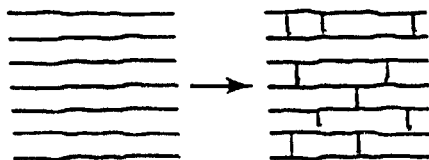
One of the properties of the crystalline regions that is of great significance to wire and cable applications is that they have a tendency to "separate" and "melt" as the temperature is raised. Such chain separation is referred to as melting. This

melting process actually occurs over a wide temperature range due to the fact that different crystalline regions have different degrees of “perfection”. Clearly, the ratio of crystalline to amorphous regions will change as a cable is thermally load cycled in service. The chain separation process leads to property changes such as: reduction in physical properties (tensile strength, elongation, modulus) and a reduction in dielectric strength. When a cable that has been subjected to thermal overload (heated to rather elevated temperatures that are defined in industry specifications) is later cooled down, the crystalline regions will reform. The physical and electrical properties will now improve. There are fine differences in the nature of the newly formed crystalline regions and the original structure, but the nature of these differences is beyond the scope of this book. The subject of thermal overload is relevant to crosslinked systems.

2.2 Crosslinked Polyethylene

Crosslinking means that the different polyethylene chains are linked together. This is shown in Figure 5-6. In a sense, XLPE can be considered to be a branched polyethylene where the branch is connected to a different PE chain instead of just “hanging loose.” Crosslinking imparts certain quite desirable properties to the PE. From a cable perspective, it allows the polymer to maintain its form stability at elevated temperatures.

Figure 5-6
Simplified Description of Crosslinked Network



As we have seen from the previous discussion, conventional polyethylene is comprised of long chain polymers that, in turn, are comprised of ethylene groups. The individual molecules are very long. The backbone may contain 10,000 to 60,000 atoms, often more. Further, we have also seen that there are crystalline and amorphous regions and that any additives or impurities must be residing in the amorphous regions -- not the crystalline regions. Crosslinking adds yet another dimension to the complexity of the molecular arrangement.

Figure 5-7
What Crosslinking Does to Chain Length of Polyethylene

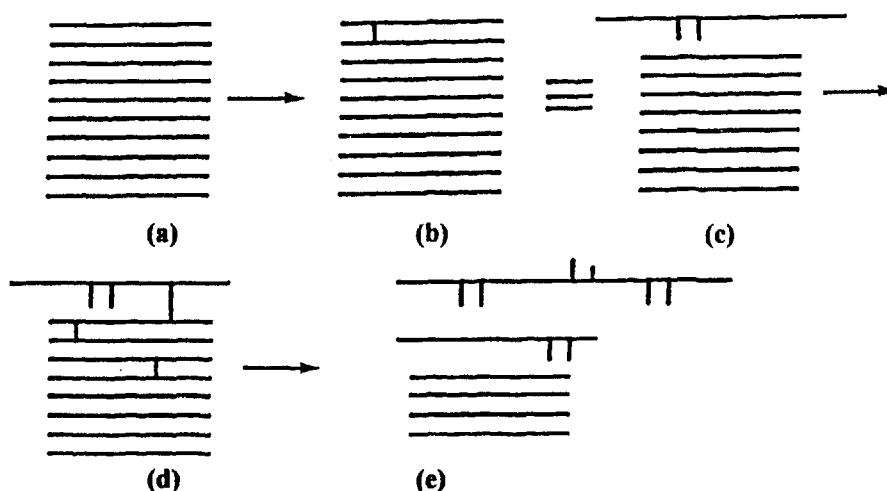


Figure 5-7 provides a description of how a conventional, non-crosslinked polyethylene “parent” is converted to the crosslinked “child”. For simplicity, the chains (a) are all shown next to each other. The linear chains represent a simplified description to fit our purposes now. First, two adjacent chains link together (b). We immediately see that the molecular weight has increased. The first crosslink leads to two branches. In (c), we have simply redrawn the first two chains from (b) in a more familiar way. In (d), we have added three additional crosslinks, two to different chains. The third shows that the newer (previously crosslinked) higher molecular weight chain is again linked to another chain. In (e), we have redrawn (d) to show how the crosslinking process looks as the chains are again “stretched out.” Note now that the original two chains have dramatically increased in molecular weight.

It should be clear from this description that the crosslinking process is a way of increasing the molecular weight. This is exactly what occurs. Note also that all the chains do not necessarily increase in molecular weight at the same rate. As the process continues (only the beginning of the process is depicted here), the molecular weight gets so great that the crosslinked polyethylene can be considered to have an “infinite” molecular weight.

One way of characterizing whether we have an extremely high molecular weight polymer or a crosslinked polymer is to check its solubility in an organic solvent

such as toluene, xylene, or decalin. A conventional polyethylene, even one of very high molecular weight, will dissolve in a heated solvent of this type. Crosslinked polyethylene will not dissolve. The solubility results from the chains moving apart in the heated solvent. The chains also move apart in the crosslinked polymer, but not so far apart so that dissolution occurs. What happens instead is that the crosslinked polyethylene merely swells in the solvent and produces a gel. Indeed, this is called the gel fraction. Another way to determine whether the PE is crosslinked or not is to subject it to heat such as by placing the sample in contact with heated silicone oil or a hot surface. The conventional PE will flow while the XLPE will resist flowing and behave more "rubbery."

Commercial XLPE insulation also possess a "sol" fraction. This is the portion of the polymer chains that never get incorporated into the "infinite" network. In Figure 5-7, we see some chains in (e) not incorporated into the network. The gel fraction of a commercial XLPE is about 70 to 80%.

Another consideration is the number of crosslinks between individual PE chains. This is referred to as the molecular weight between crosslinks and has some theoretical significance. For commercial purposes, a 70 to 80% gel fraction is an adequate description. It is common to also refer to the "hot modulus." This is a somewhat easier measurement to make than is a sol fraction and does not involve the use of organic solvents. The hot modulus is directly related to the degree of crosslinking, or more correctly to the molecular weight between crosslinks. It is greater as the degree of crosslinking increases or as the molecular weight between crosslinks decreases.

The next issue to consider is, just how is crosslinking brought about?

Crosslinking of the PE chains can be induced by several different means:

- ☐ Use of organic peroxides
- ☐ Use of high energy radiation
- ☐ Modification of the backbone structure

2.2.1 Peroxide Induced Crosslinking. Polyethylene that is crosslinked by peroxides (the most common method for medium voltage cables) contains a small amount of a crosslinking agent that is dispersed throughout the polymer. This agent is an organic peroxide. Organic peroxides are chemicals that are stable at room temperatures, but decompose at elevated temperatures. There are many such peroxides available. One peroxide, called dicumyl peroxide, is used commercially for medium and high voltage cables. It is incorporated into PE pellets by the material suppliers. When the polyethylene is extruded (conversion of the pellets into cable insulation), it remains stable due to the fact that the

decomposition temperature is higher than the extrusion temperature. After the extrusion process is complete and the PE is now surrounding the conductor and the conductor shield, the cable enters the long curing tube where the temperature is raised above the temperature employed in the extruder. At this high temperature and pressure, the peroxide now decomposes and induces the crosslinking process. Peroxide induced crosslinking uses a peroxide that is designed to intentionally decompose at a desired temperature after the conversion of the pellets into cable insulation. The tube is called a curing tube and the terms curing and crosslinking are often used synonymously. Note that this process takes place in the molten state of the insulation.

The peroxide acts by forming an active ingredient, called a free radical, that is unstable. The latter is so active that it interacts with any nearby molecule, which is virtually always the PE chain. This free radical forms when the peroxide "splits" into an active oxygen containing component that "pulls" hydrogen atoms off the polymer chains. The active "unstable" component is now the polymer chain and two such chains combine to stabilize the system once again. During this process, the peroxide decomposes and several by-products are ultimately formed. The major ones are dimethyl benzyl alcohol and acetophenone. Other ingredients may also be formed in smaller quantities such as alpha methyl styrene and methane as well as water vapor.

These by products form in the following manner. When the free radical (called cumyloxy radical) forms, it can undergo several different types of reaction in its quest to become stabilized. It can "grab" a hydrogen atom from the PE and form the relatively stable dimethyl benzyl alcohol molecule. However, the unstable radical may also undergo internal rearrangement and "kick out" a methyl radical and become acetophenone. The unstable methyl radical may also pick off a hydrogen atom from the polymer, hence forming methane gas. Water may be formed if the dicumyloxy radical kicks out a hydroxyl and hydrogen radical to form water. It is then converted to alpha methyl styrene in the process. The first three ingredients are always found in relatively large quantities in XLPE. The alpha methyl styrene is always present in smaller concentrations. It should be noted that, at times, cumene is also found as another by product. It is believed to develop from the further reaction of alpha methyl styrene.

It should be apparent by now that the crosslinking process involves rather complex reactions. To achieve a good product, the peroxide must be uniformly dispersed within the PE. For appropriate uniformity of the crosslinking process to take place in the cable insulation, proper temperature and pressure must be maintained in a tube of long but finite length. The crosslinking process described here also applies to mineral filled EPR or TR-XLPE. The same by products are produced. It must not be forgotten that the carbon black containing shields are also being crosslinked concurrently.

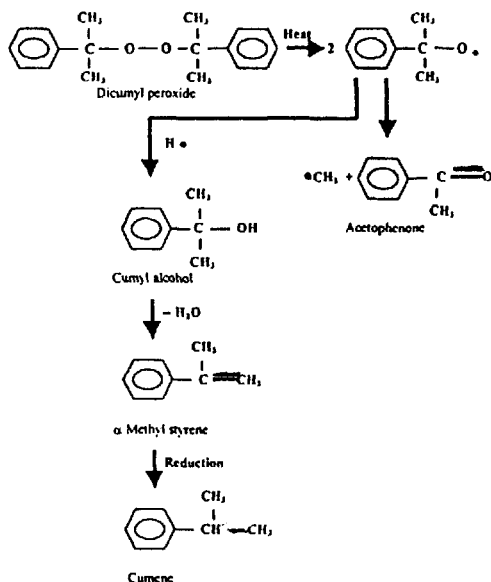
Dicumyl peroxide has been commercially available in several forms:

- ❑ Free flowing powders that contain about 40% active materials, the inert ingredients being calcium carbonate or clay as a 94 to 97% active, light yellow, semicrystalline solid.
- ❑ Or a slightly more pure 98% active grade.

Acetophenone is a low melting solid (approximately 20 degrees C) with a somewhat sweet odor. It is not soluble in water and is partially soluble in polyolefins, the extent being dependent on the temperature. Its structure is shown below in Figure 5-8 along with that of dimethyl benzyl alcohol and alpha methyl styrene.

Figure 5-8.

Decomposition of Dicumyl Peroxide Leads to Formation of Volatile By-products.



Methane forms by reaction of methyl and hydrogen radicals. It is allowed to evolve from the XLPE insulated cable. Other by-products remain and may migrate out over time.

From what we have learned above, it is clear that this process must take place in the amorphous regions since the crystalline regions cannot hold the peroxide prior to the extrusion process. This is not a complication during the extrusion

and crosslinking process since the crystalline regions melt in the heated tube. By the time the peroxide induced crosslinking takes place in the heated tube after extrusion, the entire polymer is amorphous. When the cable is cooled down after extrusion and crosslinking, recrystallization takes place. The newly formed by-products are now "forced" into the newly formed amorphous regions. It should be noted that the complex series of reactions described above do take place in polyethylene which, although melted, is still viscous.

Several points must be noted. When the PE (or EPR) is raised to an elevated temperature to manufacture the cable, it may be subjected to oxidative degradation. The polymer is subjected to temperatures significantly higher than it will experience in service. Oxidative degradation is potentially harmful as it introduces more polar materials that may influence changes in electrical properties and make the cable susceptible to failure mechanisms. To prevent this possible degradation from occurring, another material is incorporated into the polymer pellets called an antioxidant. Either an amine or phenolic-based compound is incorporated. It preferentially decomposes in the extruder and prevents/inhibits degradation of the polymer insulation. The antioxidant can be considered to be a sacrificial component that facilitates cable manufacturing. Also residing in the amorphous regions of the cable insulation will be antioxidant by-products. If not all of the peroxide and antioxidant are decomposed during the manufacturing process, small amounts of these ingredients may also be present -- again residing in the amorphous regions. It should be noted that the same events can occur with EPR insulated cables. While the entire polymer is amorphous, it is interspersed with clay and other additives.

Crosslinked polyethylene became the insulating material of choice for medium voltage cable in the late 1970s and early 1980s. It replaced conventional low density polyethylene due to its superior high temperature properties and better resistance to water treeing. Peroxide crosslinking has been the prime method of crosslinking for medium and high voltage cables as the process has been well developed and defined. For 69 kV transmission cables, peroxide crosslinked PE has also been the material of choice. At higher voltages, peroxide crosslinked PE has shared the market with conventional paper -- fluid filled cables. Other peroxides also have been used such as "vul-cup" which has a higher decomposition temperature. These higher temperature peroxides are of interest where it may be desired to extrude at higher than conventional temperatures. Such a material reduces the possibility of premature decomposition of the dicumyl peroxide that could cause processing problems. It should be noted that not all peroxides will decompose and induce crosslinking over the same temperature ranges.

For low voltage cables, peroxides may be used to induce crosslinking, but

economic factors have allowed both silane and radiation crosslinking to share the market. In this voltage range, it is not uncommon to employ conventional polyethylene since the stresses experienced by these cables are generally lower.

Once crosslinking has been performed, the polyethylene (which was complex in nature to begin with), is now even more complex. Crosslinking typically takes place with about 70 to 80 % of the polymer chains. This means that 20 to 30 % of the insulation material is not crosslinked. Typically this represents the low molecular weight fractions of the initial material. The cable insulation of the cable that is installed consists of a mixture of LDPE and PE. The properties are clearly dominated by the XLPE fraction. At elevated temperatures, the XLPE cable insulation clearly maintains its form stability and functions as anticipated. For EPR, the low molecular weight sol fraction will be an ethylene copolymer.

As noted above, there are a number of by products evolved as a result of the decomposition of dicumyl peroxide. The acetophenone and dimethyl benzyl alcohol are liquids at ambient temperature. They will remain in the insulation wall. There is some evidence that they do indeed impart a measure of water tree resistance to the insulation. One by product, methane, is a gas. The methane must be allowed to migrate out of the insulation after crosslinking has been accomplished. This is easily induced by allowing the cable to "sit" for a defined time after manufacture. Heating the finished cable shortens the time that is required.

2.2.2 High Energy Radiation. It is possible to crosslink polyethylene using high energy radiation. A beam of electrons emanating from special equipment can remove electrons from the polymer chain. this causes the reactive polymer chain to interact with another chain, hence inducing crosslinking. Radioactive isotopes can be used for the same purpose. High energy radiation causes some chemical changes that differ from those caused by peroxides. The main factor for use, or non-use, of radiation equipment is economics. This technology has been used in the low voltage area where high speeds can be attained.

2.2.3 Silane Induced Crosslinking. It is also possible to modify the polymer by introducing silane functionality. The silane interacts with moisture and leads to crosslinking of the different chains. Since moisture penetration is the key to inducing crosslinking, it is apparent that the process becomes more efficient as the wall thickness is reduced. Silane technology has had its major impact in application to secondary cables.

2.3 Tree Retardant Crosslinked Polyethylene

Over the years, many attempts have been made to improve the performance of conventional PE and, later, XLPE with regard to resistance to water treeing and

in order to attain increased life. Additives had been incorporated into these insulations for this purpose. As noted earlier, one of the XLPE agent by products, acetophenone, has been reported to facilitate resistance to water treeing. Dodecyl alcohol was employed as an additive to HMWPE in the past. The most common TR-XLPE system was made available from Union Carbide in the early 1980s. The patent literature discloses that a mixture of additives is likely to be present. Historical information from field aging combined with laboratory data, some of which has been generated under EPRI sponsorship, suggests that TR-XLPE is justified as being considered in a separate category from conventional XLPE. It should be noted, however, that many approaches may be employed in seeking to achieve tree retardant insulation materials. In contrast to solely incorporating additives into PE, or PE that is to be later crosslinked, it is possible to graft additives onto the polymer backbone, or to use a combination of both techniques. It is to be expected that not all "tree retardant crosslinked polyethylenes" will respond the same upon service or laboratory aging. Physical and electrical property data are of interest, not only after cable manufacture, but also after aging. TR-XLPE must still possess peroxide crosslinking agent and antioxidant, as does conventional XLPE and EPR.

Table 5-1
Comparison of XLPE and TR-XLPE

Crosslinked Polyethylene	Tree Retardant-XLPE
XLPE	TR-XLPE
	Tree retardant additives
Residual amounts of dicumyl peroxide	Residual amounts of dicumyl peroxide
Crosslinking agent by-products	Crosslinking agent by-products same as XLPE
Acetophenone	Acetophenone
Cumyl alcohol	Cumyl alcohol
Alpha methyl styrene	Alpha methyl styrene
Antioxidant plus some antioxidant degradation by-products	Antioxidant plus some antioxidant degradation by-products

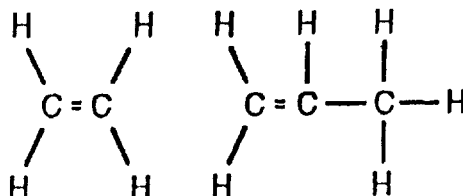
2.4 Ethylene Copolymer Insulations

When ethylene monomer is polymerized with propylene, a copolymer results that is called ethylene propylene copolymer, or EPR. The ratio of ethylene to propylene can vary over a wide range. This copolymer has significantly different properties than polyethylene. Perhaps the most significant is the fact that the propylene segments in the polymer chain interfere with the natural tendency of

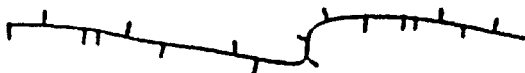
the polyethylene chains to align. The result is reduced crystallinity.

Figure 5-9

Copolymer of Ethylene and Propylene (about 50:50)



Single molecule structure



- Short chain branches
- Non crystalline-amorphous structure
- Needs reinforcing fillers (about 50%)
- Needs to be crosslinked

Sometimes, it is preferable to add a third monomer to the ethylene propylene system prior to polymerization. This is called a diene monomer, and is used to facilitate certain crosslinking processes. These materials are called EPDM. In the cable industry, it is common to call all ethylene co- or ter-polymers of this type as EPRs.

EPR materials are known as elastomers. All conventional elastomers have significantly different properties from semicrystalline polymers. Reduced crystallinity means that the property of “toughness” and high tensile strength are missing. It means that an insulation that is analogous to high molecular weight polyethylene cannot be produced with an uncrosslinked ethylene copolymer. To achieve improved physical properties, it is necessary to incorporate inorganic mineral fillers into the EPR compound. The EPR resin must also be crosslinked to render it useful as an insulation material. If it were not crosslinked, EPR would still be too soft and tacky to serve as an insulation. An EPR insulation material is generally referred to as a compound as there are several other additives that are present in EPR insulations. Once these additives are incorporated, the resin used as an insulation is referred to as a compound. The method of mixing the ingredients together is referred to as a compounding

process. Tables 5-2 shows a typical EPR formulations supplied commercially. It should be noted that many EPR compounds that are used as insulations for cables are proprietary and the formulations are not published.

Table 5-2
Nordel Based EP Insulation Compounds in Parts per Hundred

Ingredient	Amorphous	Semicrystalline
Nordell 1040 (amorphous)	100.0	
Nordell 2722 (semicrystalline)		100.0
Low density PE		5.0
Zinc oxide	5.0	5.0
Red lead (90% dispersion)	5.0	5.0
Silane treated Kaolin	120.0	60.0
Vinyl silane A-172	1.0	1.0
Process oil	15.0	
Paraffin wax	5.0	5.0
Antioxidant	1.5	1.5
Dicumyl peroxide	3.5	2.6

The purpose of the various ingredients (published EPR formulations) are noted below:

- ☐ **Ethylene Propylene Co- or Ter-polymer.** This is the base material that forms a continuous phase in which all the ingredients noted below are uniformly dispersed. This controls the flexibility of the final formulation.
- ☐ **Inorganic Mineral Filler.** This is a coated clay that serves to improve the mechanical properties of the formulation. Since the rubber material has little or no crystallinity, the filler serves the purpose of providing mechanical strength. The clay is coated with a silane material to improve polymer-filler interaction at the interface. The filler particles are extremely large compared to the polymer chain.
- ☐ **Zinc Oxide.** A traditional component in EPR and EPDM compounds that was initially incorporated into cable insulation as it was used in automobile tire formulations.
- ☐ **Ion Scavenger.** This is known as "red lead" or lead oxide. It improves electrical properties under wet aging. Incorporated many

years ago to meet low voltage cable test requirements.

- ☐ **Crosslinking Agent.** Generally dicumyl peroxide. It serves the same role as it does in XLPE.
- ☐ **Processing Aids.** Generally a wax or oil that is incorporated to improve the processing of the formulation during extrusion since the inorganic additives are "abrasive".
- ☐ **Antioxidant.** Serves the same roll as it does in PE or XLPE to prevent polymer decomposition during extrusion.

Additional silane may be added to assure adequate polymer/filler interaction. In addition to all these, individual manufacturers may have proprietary ingredients in the EPR formulations. These can serve various purposes such as to further enhance processing, enhance aging properties, or modify dielectric properties.

It is also possible to incorporate a third monomer into the ethylene/propylene mixture when polymerization takes place. This is sometimes referred to as "diene monomer," and the term EPDM is used to describe the resins. In the wire and cable industry, both of these types of elastomers are referred to as "EPRs." It should be noted that the difference is indeed commonly noted when accessories are studied. The diene ter-polymer is used in formulations where the unsaturation in the polymer chain is desired, such as for specialized methodology where the unsaturation of the third monomer is preferred or required.

All EPR compounds must be crosslinked to be useful as insulation, as noted above. The process for inducing crosslinking is exactly the same as for medium voltage XLPE cables. Peroxide induced crosslinking is also used for low voltage EPR insulated cables. It is not common to use silane processing for EPR although radiation crosslinking is not uncommon.

Processing of medium voltage EPR insulated cables is performed on the same equipment used for XLPE or TR-XLPE. Steam or dry curing may be employed, although steam curing is more common for EPR.

3. PAPER INSULATED CABLES

The oldest type of insulation still used for power cables is paper. Paper must be impregnated with a dielectric fluid -- initially oil obtained from cracking of petroleum, and now synthetic fluid. This section reviews the fundamentals of paper as an insulation.

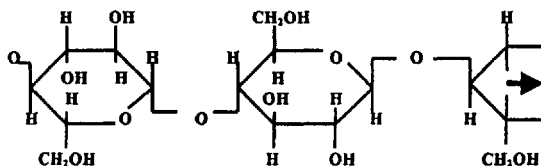
Paper is derived from wood for cable insulation. It consists of three major ingredients:

About 40%	Cellulose
About 30%	Hemicellulose
About 30%	Lignin

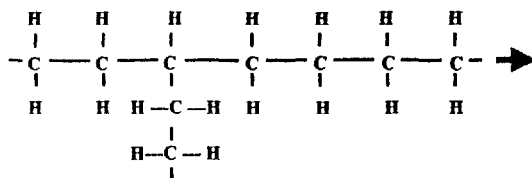
The cellulose is of interest as an insulating material and must be separated from the other ingredients by bleaching with sulfates or sulfites. The hemicellulose is a non-fibrous material, is more polar than cellulose and hence more lossy. A very low level of hemicellulose is preferred in the final material, but some quantity remains after the bleaching process. (It can be noted that cotton is pure cellulose. If cotton were used as a source for paper, no hemicellulose would be present.) The lignin is an amorphous material and serves as a binder for these components. It is removed in the manufacture of the tape. Details of the process of converting wood into a useful insulation material are beyond the scope of this book, but it should be noted that the process is well developed and has been used for scores of years.

The chemical structure of paper is shown in Figure 5-10. For comparison, polyethylene is also shown. The differences are apparent. Note that cellulose has a saturated cyclic structure (five carbons and one oxygen in a ring) and this is absent in polyethylene. In contrast to polyethylene, it is more common to refer to the molecular weight of cellulose in terms of degree of polymerization, or "DP." The DP represents the number of individual cellulose molecules in a chain. The DP of a typical cellulose molecule in wood is about 10,000. The cellulose consists of fibrils, and as noted above, it is converted into paper by the conventional processes used in the paper industry. When used as an insulation for cable, the paper is impregnated with dielectric fluids--low molecular weight hydrocarbons. As with polyethylene, these oils or fluids consist solely of carbon and hydrogen.

Figure 5-10
Chemical Structure of Cellulose



Chemical Structure of Polyethylene



4. SHIELDS

Polymers used for shields are ethylene copolymers. They may be copolymers with propylene or with other monomers such as vinyl acetate or ethyl acrylate. Each of these other co-monomers imparts different properties to the polymeric shields. As with insulation, one must consider molecular weight and molecular weight distribution issues, but crystallinity is not an issue. In addition, it is necessary to incorporate an adequate amount of a conducting carbon black into the copolymer to achieve the required semiconducting properties. One must assure appropriate particle to particle contact. It is possible to incorporate yet additional additives. For example, controlled strippability of insulation shields may be achieved with additional additives, but such additives would not be used for conductor shields where strippability is not desired.

5. JACKETS

Jackets are used over the cable to impart abrasion resistance and to protect the cable from local environment. Ideally, a jacket will aid in keeping water and foreign ions out of the insulation. Jacketing materials have varying properties that is controlled by their molecular structure and compound ingredients.

For medium voltage cables, several polyethylene types are used as jacketing materials:

Low density	(LDPE)
Medium density	(MDPE)
High density	(HDPE)
Linear low density polyethylene	(LLDPE)

It is clear by now that the differences between the first three are in the amount of "chain alignment" that takes place and that HDPE is more crystalline than is LDPE. As the name implies, MDPE is in-between the others in crystallinity.

HDPE is manufactured by a different process than are the low and medium polyethylenes. The higher the degree of crystallinity, the greater the toughness and abrasion resistance, but the more complex is the extrusion process. LLDPE is manufactured in such a manner that it approaches HDPE in properties, but by a less expensive method of manufacture.

The moisture resistance of the different PE types will vary with the degree of crystallinity. See Table 5-3.

Table 5-3
Moisture Vapor Transmission Rates

Material	Density	Moisture Vapor Transmission Rate
LDPE	0.92	1.16
MDPE	0.93	0.51
HDPE	0.94	0.58
HDPE	0.95	0.32
LLDPE	0.92	0.74
PVC	1.30	10.0
Semicons	1.15	5.00

PVC (polyvinyl chloride) is a material that was used as a jacket. Although PVC by itself is a very ridged material, it becomes quite flexible when plasticizers are added. A typical plasticizer could be dioctyl phthalate. Plasticized PVC, while providing some degree of protection against dig-ins and corrosion protection, has very poor abrasion resistance and very poor resistance to water migration. PVC is now rarely used as a cable jacket for underground distribution cables even though it is quite inexpensive relative to other materials. For low voltage cables, it is common to use other materials such as Neoprene (poly chloroprene) or Hypalon (chlorosulphanated poly-ethylene).

6. COMPARISON OF INSULATING MATERIALS

Since paper insulation was used first in the power industry, and was later replaced in low and medium voltage applications, any comparison of properties usually employs the paper-fluid system as the standard.

Table 5-4
Major Differences Between Paper and Polyolefinic Insulations

Paper / Cellulose	Polyethylene
Natural	Synthetic
Carbon / hydrogen/oxygen	Carbon / hydrogen/oxygen
More polar / medium losses	Less polar, low losses
Chains linear	Chains branched
Fibrils	Non-fibrils
Partially crystalline/ Relatively constant	Partially crystalline/ Varies with grade employed
No thermal expansion on heating	Significant thermal expansion
Not crosslinked	Not crosslinked
Thermal degradation via cleavage at weak link	Degrades at weak links

Crosslinked Polyethylene	Ethylene Propylene Rubber
Synthetic	Synthetic
Carbon / hydrogen	Carbon / hydrogen
Less polar, low losses	Losses due to additives
Chains branched, crosslinked	Chains branched, crosslinked
Non-fibril	Non-fibril
Slightly less crystalline vs PE	Least crystalline of all
Same thermal expansion as PE	Slight thermal expansion
Crosslinked	Crosslinked
Degrades at weak links	Same as XLPE

Table 5-4 provides a comparison of the properties of paper, polyethylene, crosslinked polyethylene, and ethylene propylene rubber insulations. Only the paper is a natural polymer and is therefore processed differently. Paper is obtained from a wood or cotton source. The synthetic polymers are produced by polymerization of monomers derived from petroleum. All consist of carbon and hydrogen, but paper also contains oxygen. The latter is present as functional hydroxyl or ether groups. The contribute a measure of polarity that is absent in the synthetic polymers. (Polarity means increased dielectric losses.) Of special note is the concept of thermal expansion during heating. While all of the synthetic polymers undergo thermal expansion during heating, this does not

occur with cellulose—although the oil will do so. How these insulations respond on aging is a well studied subject since it is directly related to reliability of the cable after installation and energization. When cellulose degrades, it does so at a “weak link,” the region of the oxygen linkage between the rings. When this happens, the DP is reduced. On the other hand, polyolefins degrade by a completely different mechanism—oxidative degradation at specific sites. Protection against degradation is imparted to polyolefins by adding an antioxidant to the pellets prior to extrusion. Note that adding antioxidants to oil to prevent it from degrading is rather common.

One further point should be noted on the chart: the different response of the insulation types to dc testing. DC testing of cables has traditionally been performed to ascertain the state of the cable at specific times during their use, such as before peak load season. This is a technique that was adopted for PILC cables many years ago. This was later carried over to extruded dielectric cables. Research and development in the past few years has shown that PE and XLPE may be harmed by the use of a dc test, but this does not occur with paper-oil systems. EPR cables have not been studied to the same extent and no conclusions can be drawn at this time about the effect of dc testing on the insulation.

Advantages of polyethylene:

- Low permittivity (low dielectric constant)
- Low tan delta (low dielectric loss)
- High initial dielectric strength

Advantages of crosslinked polyethylene (in addition to the ones above):

- Improved mechanical properties at elevated temperature
- No melting above 105 °C but thermal expansion occurs
- Reduced susceptibility to water treeing

Advantages of EPR:

- Reduced thermal expansion relative to XLPE
- Reduced sensitivity to water treeing
- Increased flexibility

Advantages of PILC:

- Lack of sensitivity to dc testing
- Known history of reliability

Particular advantages of synthetic polymer insulations over PILC:

- Reduced weight
- Accessories more easily applied
- Easier to repair faults
- No hydraulic pressure / pumping requirements
- Reduced risk of flame propagation
- Reduced initial cost

Some of these advantages are electrical and some are not.

Care must be taken in seeking to compare EPR to XLPE to TR-XLPE. There are many different EPR formulations. The nature of the non-polymeric additives, including fillers, plays a major role in influencing properties as well as the nature of the mixing process. What is clear is that any EPR formulation will have higher losses than a non-mineral filled PE or XLPE system. Some EPR systems may have very high losses. This may influence resistance to water treeing. However, EPR systems are generally “softer” due to their lack of crystallinity and therefore easier to handle in the field—especially at very low temperatures.

Disadvantages to PILC include the fact that lead is usually used as an outer sheath and the motivation not to use lead for new installations is very high. Paper is also highly susceptible to deterioration from moisture.

7. REFERENCES

[5-1] Bruce S. Bernstein, adapted from class notes from “Power Cable Engineering Clinic,” University of Wisconsin–Madison, 1997.

[5-2] Kenneth N. Mathes, adapted from class notes from “Power Cable Engineering Clinic,” University of Wisconsin–Madison, 1995.

[5-3] *Textbook of Polymer Science*, F. W. Billmeyer, John Wiley and Sons.

[5-4] EPRI Report EL-4398, “Long Life in Cable Development: Extruded Cable Materials Survey,” March 1986.

[5-5] EPRI Report EL-4201, “Long Life Cable Development: Processing Survey,” September 1985.

- [5-6] Bruce S. Bernstein, "Cable Testing: Can We Do Better?" IEEE Electrical Insulation Magazine, Vol. 10, No. 4, July/August 1994.
- [5-7] EPRI Report TR-106680, "EPR Cable Insulation Study," August 1996.
- [5-8] EPRI Report EL-1854, "Evaluation of Cable Insulation Materials," May 1981.
- [5-9] B. Thornburn, "Electron Beam Crosslink Technology," Wire Journal International, July 1993.
- [5-10] A. Zamore, "Moisture Curable Wire and Cable Compounds," Wire Journal International, September 1996.
- [5-11] B. S. Bernstein and R. W. Samm, "Influence of Temperature on Accelerated Aging of XLPE and EPR Insulated Cables," Paper A.8.5, Proceedings Jicable '95, Paris, France, June 1995.
- [5-12] Southwire Company, "Power Cable Manual," Chapters 3, 4, and 5, 1991.
- [5-13] T. O. Kressner, *Polyolefin Plastics*, Van Nostrand Reinhold Company, 1969.